GEOPHYSICAL RESEARCH LETTERS, VOL. 27, NO. 24, PAGES 3993-3996, DECEMBER 15, 2000

Resolution of tomographic models of the mantle beneath Iceland

William R. Keller, Don L. Anderson, and Robert W. Clayton

Department of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California

Abstract. The locations of volcanic islands may be controlled by thin or extending parts of the lithosphere over a partially molten asthenosphere [*Anderson and Bass*, 1984; *Favela and Anderson*, 2000], by edge effects near the boundaries of thick cratonic lithosphere [*Anderson*, 1998], or by narrow jets of hot mantle rising from deep within the mantle [*Campbell and Griffiths*, 1992; *Morgan*, 1971; *Wilson*, 1986]. Many hotspots are found on or near ridges, at lithospheric discontinuities, or in extensional environments, so high resolution seismic images are required to determine whether it is lithospheric structure, stresses in the lithosphere, or the deep mantle that is the controlling factor for the location of these volcanoes. In this study, we perform a simple experiment in which we use basic geometrical arguments to better understand the resolution of tomographic images of the upper 400 km of the mantle under Iceland. Our results indicate that a narrow, deep seated mantle plume is not required in order to explain the observed travel time delays in this region. Results of tomographic inversions are often viewed as unique; however, recent seismic studies of the Icelandic Hotspot have illustrated the non-unique nature of these models.

1. Introduction

Plume geometry in laboratory and computer simulations is, in its most simple form, a narrow cylinder capped by a bulbous head which flattens beneath the lithosphere, giving an overall mushroom shape to the upwelling [*Feighner et al.*, 1995; *Kincaid et al.*, 1996; *Sleep*, 1994]. Deep mantle upwellings are also expected to broaden beneath the 650 km endothermic phase change [*Davies*, 1995; *Liu et al.*, 1991; *Machetel and Weber*, 1991]. The geometry of upwellings driven by plate divergence or by lateral changes in lithospheric thickness are expected to be focused at the surface toward thin or extending regions. Iceland is in a particularly complex region, different from other volcanic islands, because it is located on a very slowly spreading ridge in the youngest, narrowest part of the Atlantic Ocean and is bounded by thick cratonic lithosphere. The separation of thick cold cratonic lithosphere will generate a deep upwelling which focuses toward the surface to fill in the newly formed gap [*Anderson*, 1998]. Passive steady-state upwellings, such as those found at mature ridges away from thick cratonic lithosphere, will exhibit a similar geometry but will not have as deep of an expression. Ribe et al. [1995] showed that a hot ($\Delta T \sim 250°C$) and narrow ($a \sim 60$ km) plume rising underneath Iceland would produce a bathymmetric signature that is inconsistent with observations [*Vogt et al.*, 1980]. They found that the anomaly must be cooler ($\Delta T < 100°C$) and wider ($a > 300$ km) than would be expected from a hot rising plume. Using seismic methods, it is theoretically possible to distinguish between a narrow plume upwelling, passive effects due to plate divergence, and dynamic upwelling between two cratons; however, distinguishing between these three scenarios is problematic with real data.

Using data from a regional broadband seismic experiment (ICEMELT), Wolfe et al. [1997] produced three dimensional tomographic images of the mantle beneath Iceland which show a "cone shaped" low velocity zone beneath the island that is approximately 150 km wide at the surface and is inferred to extend to at least 400 km depth. They suggest that this low velocity zone is the expression of a plume that is rising from deep within Earth's mantle. However, this "cone shaped" geometry is not consistent with published laboratory and computer generated images of plumes that suggest the existence of a cylindrical plume conduit which feeds a broadening plume head in the uppermost mantle. The "cone shaped" tomographic appears to be defined by the cone of incoming rays, and most of the rays are traveling at incidence angles ranging from near vertical to approximately 40 degrees from vertical in the upper 400 km beneath Iceland. Because of the lack of crossing rays, the structure described might be explained by the smearing out of a shallow (<200 km depth) low velocity anomaly instead of the effect of a deep mantle plume.

This is the well known parallax problem and is not unlike the problems encountered when a light is shone on an object and one attempts to reconstruct the shape of the object from the shadow it forms on the wall. For instance, a disc, a sphere, an ellipsoid, a cone, and a cylinder will all cast a circular shadow on the wall when oriented in the proper way. The only way to determine the three dimensional shape of the object is to observe the shadow when the light source is shone on the object at widely varying angles. We show that the uniqueness and resolution problem encountered when imaging the Icelandic mantle is due to the geometry of the experiment and the lack of crossing ray information. Other tomographic studies in areas near hotspots have found that it is impossible to distinguish between a shallow anomaly in the upper 200 km of the mantle and a narrow deep seated plume due to experimental geometry. In a recent study of the Yellowstone Hotspot, Saltzer and Humphreys [1997] found that both scenarios fit their tomographic inversion results equally well.

2. Method and Results

We perform simple tomographic resolution tests in which we calculate idealized synthetic delay times for S-waves

Paper number 2000GL011798.
0094-8276/00/2000GL011798$05.00

through a variety of velocity anomalies in the upper 400 km of the mantle, and then we invert these delays for structure in order to understand how well these anomalies may be resolved in a tomographic inversion. Raypaths from sources and receivers along the two dimensional profile discussed in Wolfe et al. [1997] were calculated to determine the ray coverage, number of ray crossings, and angle of ray crossings along this cross section of the model. The sources and receivers used in this calculation are shown in red in figure 1a and 1b. The sources shown in light red are the earthquakes that occurred further than 90 degrees from Iceland. For simplicity, sources beyond 90 degrees that are off of our profile are not shown. The profile shown in yellow in figure 1 is a "best case scenario" because it contains the widest range of source to receiver offsets of any profile in the data set, and thus it contains the best ray crossing information. We expect this cross-section to provide an upper bound on the resolution of the full 3D analysis because it has more constraints per degree of freedom than the full model. In addition, all of the possible source – receiver combinations were used in our calculations which gives an optimistic resolution estimate given the fact that data recovery during seismic experiments is rarely, if ever, one hundred percent. Slightly less than half of the possible S-wave source receiver combinations in the ICEMELT experiment [*Wolfe et al.*, 1997] yielded useful data in which accurate travel time measurements could be made. Figure 2a shows that most of the rays in the upper 400 km of this model occur at steep angles of incidence, and most of the angles between crossing rays are small. Vertical exaggeration of 2:1 is used in our figures to facilitate comparison to published images by Wolfe et al. [1997].

For the resolution tests, we cast a model with a cartesian grid which has a spacing of 50 km in the horizontal direction and a spacing of 25 km in the vertical direction. To simplify the resolution tests, it is assumed that the raypaths are straight lines in the upper 400 km of the mantle and that the cartesian grid is a good approximation to a spherical earth in the region of interest. On indication that this assumption is reasonable is the fact that the curvature of the rays shown in figure 2a is very small. A pseudo hit count map for the tests is shown in figure 2b. There is a strong correlation between figure 2b and the tomographic inversion results along this profile (figure 3b2, Wolfe et al. [1997]), and this illustrates the biased nature of the result of the inversion.

A narrow deep low velocity anomaly (figure 3a1) and a broader shallow low velocity anomaly (figure 3b1) were used as starting models in the resolution tests. After synthetic travel time delays were calculated through both of these models along the profile in question, the delay times were inverted for structure. A generic SIRT (Simultaneous Iterative Reconstruction Technique) algorithm was used for this inversion [*Humphreys and Clayton*, 1988], and the results are shown in figure 3a2 and figure 3b2. Elements in which there is no ray coverage are black. The large amount of vertical smearing shown in figure 3b2 indicates that the depth resolution of this dataset is very poor. The inversions performed in each resolution test yield results which satisfy the synthetic travel time delays equally well, thus neither a deep anomaly or a shallow anomaly are favored by tomographic inversions. Figure 3a2 shows that the horizontal resolution of the inversion is quite good and that the narrow plume structure is recovered accurately. Wolfe et al. suggest that inverting for a narrow plume structure (figure 3a1) may cause artificial broadening by as much as 50 percent; however, there is little artificial broadening of the structure in our resolution tests. The structure obtained by inverting for a broader shallow structure actually resemble the inversion results of Wolfe et al. more closely than the results of inverting a narrow deep anomaly. The two starting models used for our resolution tests are simply two possibilities for the structure of the mantle beneath Iceland. It is quite possible that other starting models could explain the data equally well. The different hypotheses proposed for the mantle structure beneath Iceland are indistinguishable because of the geometry of the experiment.

3. Discussion

In addition to using seismic tomography to infer the depth extent of proposed plumes, various authors have attempted to constrain the depth extent of these anomalies by analyzing PdS conversions, waves converted from P to S at seismic discontinuities at depths, d, below the receiver. Shen et al. [1998] showed that P660s-P410S differential times in Iceland are less than predicted, which indicates either a fast or a thin transition zone in this region. They conclude that their observations are most consistent with thinning of the transition zone through interaction with a hot narrow plume originating from the lower mantle. However, they are not able to rule out the possibility of a larger regional anomaly because the area southeast of Iceland remains largely unmapped by their techniques. Shen et al. [1998] observe a relatively small area of anomalous P660S-P410S differential times, and their preferred model is that of a narrow plume which travels unimpeded through the transition zone, with no change in shape. However, numerical modeling has shown that plume conduits are expected to broaden just below the endothermic phase change at 660 km and to narrow as they enter the low viscosity region of the upper mantle [*Brunet and Yuen*, 2000; *Davies*, 1995; *Liu et al.*, 1991; *Machetel and Weber*, 1991]. In light of these results, interaction with a hot mantle plume will cause the transition zone to be thinned over a large region as a result of the broad upwarping of the 660 km discontinuity which is overprinted by a relatively narrow downwarping of the 410 km discontinuity. Dueker and Sheehan [1997] found transition zone thickness variations across the Yellowstone Hotspot track that are similar in magnitude to that found by Shen et al. [1998] in Iceland. Dueker and Sheehan [1997] also found that the topography of the 410 km and 660 km discontinuities are not anticorrelated as would be expected if this thinning were caused by interaction with a mantle plume. Other studies have shown no evidence for correlation between thin transition zone and proposed hotspot locations. Vinnik et al. [1997] looked at PdS conversions for hotspots on the Pacific Plate and found no evidence for thin transition zone under known hotspots. Chevrot et al. [1999] analyzed PdS conversions from over 80 stations and 9 locations near hotspots, including Iceland, and they concluded that there was no correlation between transition zone thickness and location of hotspots on a global scale.

Recent tomographic studies in Iceland have also yielded varied results. Bijwaard and Spakman [1999] published the results of a global tomographic model in which they focused on an area of low velocity below Iceland they suggest extends

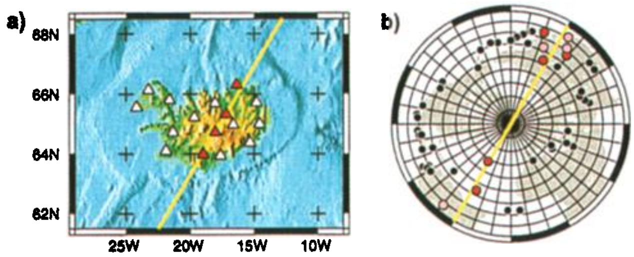

Figure 1. a) Location of the seismic instruments used in the ICEMELT experiment. The yellow line marks the location of the cross section shown by Wolfe et al. [1997], the cross section used for all the calculations in this study. The receivers used in our 2D calculations are shown in red on this figure. b) Location of the earthquakes recorded during the ICEMELT experiment. The sources used in this study are shown in red (sources beyond 90 degrees which were used in our resolution tests are shown in light red), and the azimuth of our 2D profile is again shown in yellow. All possible source – receiver combinations are used in our calculations which gives an upper bound on resolution.

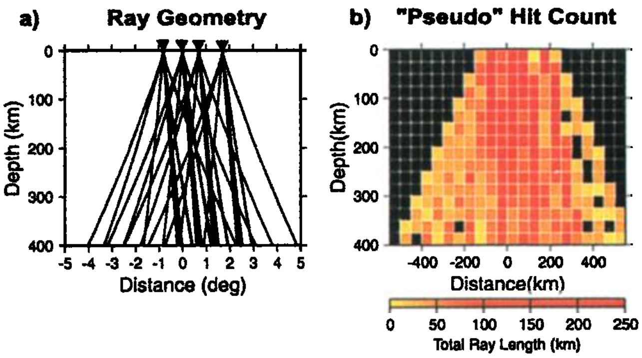

Figure 2. a) Plot showing all the rays used for the calculations in this study. The rays range from being nearly vertically incident to approximately 40 degrees from vertical. There is very little ray crossing information at depth, especially in the SW side of the model (left side of figure). Vertical exaggeration is included in our figures for the purpose of comparison to the Wolfe et al. [1997] model. b) This figure shows the cumulative ray length for each element in our model, and can be thought of as a pseudo hit count. This image bears a strong resemblance to tomographic inversion results along this profile, illustrating the biased nature of the inversion results. PREM is the reference model that is used in all calculations in this study [*Dziewonski and Anderson*, 1981].

from the core-mantle boundary to the surface. Their model shows that the imaged structure is very complex with numerous lateral branches. The plume head in their model encompasses the entire upper mantle of the North Atlantic Region; however, regional tomographic studies in Iceland [*Pritchard et al.*, 1999; *Wolfe et al.*, 1997] have confirmed the existence of a low velocity anomaly with a diameter less than that of the island. Pritchard et al. [1999] suggest that the velocity anomaly in the upper mantle beneath Iceland actually narrows with depth in a cross section perpendicular to the Mid-Atlantic Ridge as opposed to broadening with depth like the cone shaped anomaly of Wolfe et al. [1997]. They also show an anomaly that is elongated in a N-S direction along

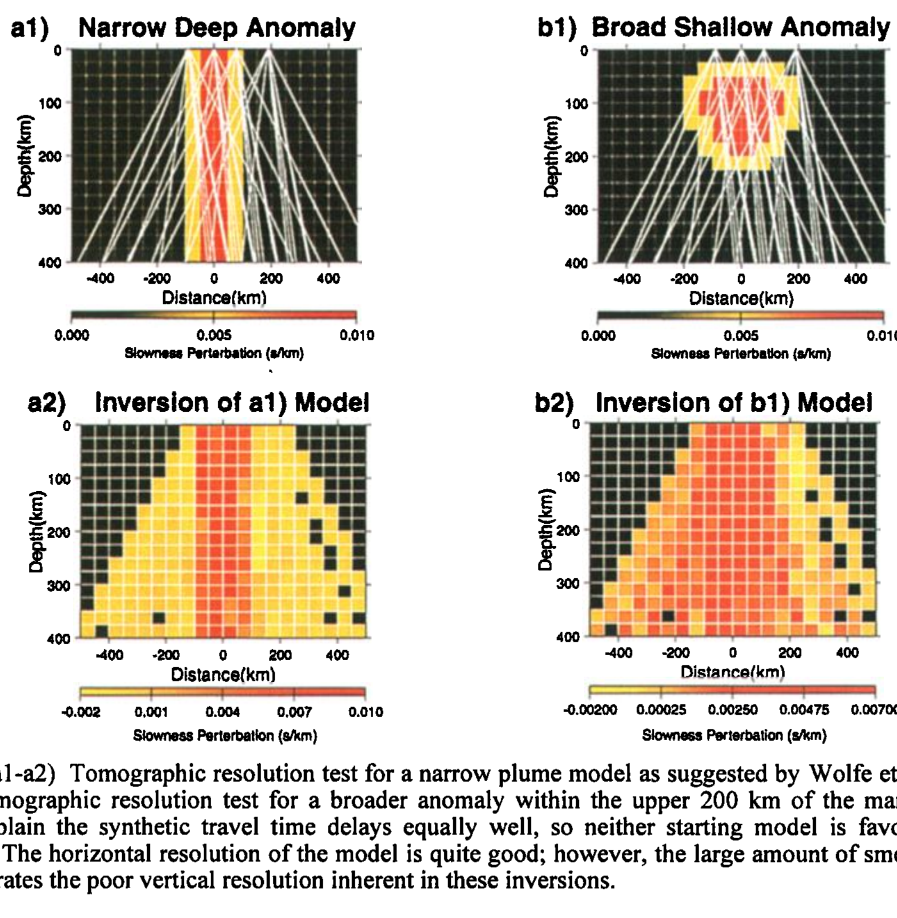

Figure 3. a1-a2) Tomographic resolution test for a narrow plume model as suggested by Wolfe et al. [1997]. b1-b2) Tomographic resolution test for a broader anomaly within the upper 200 km of the mantle. Both models explain the synthetic travel time delays equally well, so neither starting model is favored in the inversion. The horizontal resolution of the model is quite good; however, the large amount of smearing seen in b2 illustrates the poor vertical resolution inherent in these inversions.

the ridge axis at depth as opposed to the axially symmetric model of Wolfe et al. [1997]. The model of Ritsema et al. [1999] shows a broad upper mantle anomaly, but there is no indication that the anomaly extends deeper than 670 km. Varying experimental parameters, assumptions, geometry, number of crossing rays, and inversion techniques have clearly had a major effect on the results of these different tomographic models of the Icelandic mantle.

It is evident that the problems involved in resolving vertical structure in the mantle beneath Iceland is greatly limited by two factors – the small aperture of the seismic array as a result of the limited dimensions of the island, and the steep incidence of rays in the upper 400 km - caused by a relative lack of seismicity close to Iceland and the decision to only use sources greater than 30 degrees away from the receiver array. These same factors limit the effectiveness of seismically imaging other oceanic hotspots because of the generally small diameter of ocean islands and because of the relative lack of sizeable earthquake sources within the ocean basins. It is apparent that the resolution of regional tomography experiments must be improved in order to successfully determine whether lithospheric structure, stresses within the lithosphere, or the deep mantle is the controlling factor in the formation of proposed hotspots. Ray crossing information and thus the resolution of such images could be increased by expanding the aperture of the array by using ocean bottom seismometers, by using events within 30 degrees of the island as opposed to limiting the data to teleseismic events, and by including travel times from phases such as SS, sS, and ScS as was done by Pritchard et al. [1999]. Results of tomographic inversions are often treated as unique; however, in the case of the Icelandic mantle, several groups have obtained very different results by using different assumptions, inversion techniques, and data sets. These discrepancies highlight the non-unique nature of seismic tomography and point out the importance of publishing several possible results of any given tomography experiment either in print, or in supplemental information made available electronically.

Acknowledgments. We thank Gillian Foulger, Bruce Julian, Cecily Wolfe, and Sean Solomon for insightful discussions and comments. This paper represents Contribution Number 8704, Division of Geological and Planetary Sciences, California Institute of Technology. This work has been supported by NSF grant EAR 9726252.

References

Anderson, D.L., The Edges of the Mantle, in *Geodynamics Series*, edited by M. Gurnis, M.E. Wysession, E. Knittle, and B.A. Buffett, pp. 255-271, 1998.

Anderson, D.L., and J.D. Bass, Mineralogy and composition of the upper mantle, *Geophysical Research Letters, 11* (7), 637-640, 1984.

Bijwaard, H., and W. Spakman, Tomographic evidence for a narrow whole mantle plume below Iceland, *Earth and Planetary Science Letters, 166* (3-4), 121-126, 1999.

Brunet, D., and D.A. Yuen, Mantle plumes pinched in the transition zone, *Earth and Plantetary Science Letters, 178*, 13-27, 2000.

Campbell, I.H., and R.W. Griffiths, The changing nature of mantle hotspots through time; implications for the chemical evolution of the mantle, *Journal of Geology, 100* (5), 497-523, 1992.

Chevrot, S., L. Vinnik, and J.-P. Montagner, Global-scale analysis of the mantle Pds phases, *Journal of Geophysical Research, 104* (9), 20,203-20,219, 1999.

Davies, G.F., Penetration of plates and plumes through the mantle transition zone, *Earth and Planetary Science Letters, 133* (3-4), 507-516, 1995.

Dueker, K.G., and A.F. Sheehan, Mantle discontinuity structure from midpoint stacks of converted P to S waves across the Yellowstone hotspot track, *Journal of Geophysical Research, B, Solid Earth and Planets, 102* (4), 8313-8327, 1997.

Dziewonski, A.M., and D.L. Anderson, Preliminary reference Earth model, *Physics of the Earth and Planetary Interiors, 25* (4), 297-356, 1981.

Favela, J., and D.L. Anderson, Extensional Tectonics and Global Volcanism, *in press*, 2000.

Feighner, M.A., L.H. Kellogg, and B.J. Travis, Numerical modeling of chemically buoyant mantle plumes at spreading ridges, *Geophysical Research Letters, 22* (6), 715-718, 1995.

Humphreys, E., and R.W. Clayton, Adaptation of back projection tomography to seismic travel time problems, *Journal of Geophysical Research, 93* (2), 1073-1085, 1988.

Kincaid, C., J.G. Schilling, and C. Gable, The dynamics of off-axis plume-ridge interaction in the uppermost mantle, *Earth and Planetary Science Letters, 137* (1-4), 29-43, 1996.

Liu, M., D.A. Yuen, W. Zhao, and S. Honda, Development of diapiric structures in the upper mantle due to phase transitions, *Science, 252* (5014), 1836-1839, 1991.

Machetel, P., and P. Weber, Intermittent layered convection in a model mantle with an endothermic phase change at 670 km, *Nature, 350* (6313), 55-57, 1991.

Morgan, W.J., Convection plumes in the lower mantle, *Nature, 230* (5288), 42-43, 1971.

Pritchard, M.J., G.R. Foulger, B.R. Julian, J.R. Evans, R.E. Allen, G. Nolet, W.J. Morgan, B.H. Bergsson, P. Erlendsson, S. Jakobsdottir, S. Ragnarsson, R. Stefansson, and K. Vogfjord, A Teleseismic tomography Image of the Iceland Mantle Plume, *EOS Transactions, AGU, 80*, F646, 1999.

Ribe, N.M., U.R. Christensen, and J. Theissing, The dynamics of plume-ridge interaction; 1: Ridge-centered plumes, *Earth and Planetary Science Letters, 134* (1-2), 155-168, 1995.

Ritsema, J., H.J. van Heijst, and J.H. Woodhouse, Complex shear wave velocity structure imaged beneath Africa and Iceland, *Science, 286* (5446), 1925-1928, 1999.

Saltzer, R.L., and E.D. Humphreys, Upper mantle P wave velocity structure of the eastern Snake River plain and its relationship to geodynamic models of the region, *Journal of Geophysical Research, 102* (6), 11,829-11,841, 1997.

Shen, Y., S.C. Solomon, I.T. Bjarnason, and C.J. Wolfe, Seismic evidence for a lower-mantle origin of the Iceland Plume, *Nature, 395* (6697), 62-65, 1998.

Sleep, N.H., Lithospheric thinning by midplate mantle plumes and the thermal history of hot plume material ponded at sublithospheric depths, *Journal of Geophysical Research, 99* (5), 9327-9343, 1994.

Vinnik, L., S. Chevrot, and J.-P. Montagner, Evidence for a stagnant plume in the transition zone?, *Geophysical Research Letters, 24* (9), 1007-1010, 1997.

Vogt, P.R., G.L. Johnson, and L. Kristjansson, Morphology and magnetic anomalies north of Iceland, *Journal of Geophysics, 47* (1-3), 67-80, 1980.

Wilson, J.T., Continental Drift, *Scientific American, 208* (4), 86-100, 1986.

Wolfe, C.J., I.T. Bjarnason, J.C. VanDecar, and S.C. Solomon, Seismic structure of the Iceland mantle plume, *Nature, 385* (6613), 245-247, 1997.

William R Keller, Don L. Anderson, and Robert W. Clayton, Division of Geological and Planetary Sciences, California Institute of Technology, Mail Code: 252-21, Pasadena, California 91125. (e-mail: keller, dla, or clay@gps.caltech.edu)

(Received May 18, 2000; revised August 15, 2000; accepted September 27, 2000.)